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Posted Date: 4 March 2026

doi: [10.20944/preprints202603.0290.v1](https://doi.org/10.20944/preprints202603.0290.v1)

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Article

Do Ecological Patterns Persist in Highly Impacted Urban Wetlands? A Spatiotemporal Analysis of Aquatic Macrophytes and Limnological Variability in a Peruvian Coastal Wetland

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Abstract

Urban coastal wetlands along the Peruvian Pacific coast are increasingly affected by urban expansion, pollution, and hydrological alterations, compromising their ecological integrity. In this context, the spatiotemporal variation of the aquatic macrophyte community and its relationship with limnological conditions and drivers of change were evaluated in the Santa Rosa wetland (Chancay, Lima). The objective is to evaluate the spatiotemporal variation of the aquatic macrophyte community in the Santa Rosa wetland and analyze its relationship with physicochemical limnological variables and drivers of change. Sampling was conducted during two contrasting hydrological seasons in 2022: T1 (summer) and T2 (winter), at six sampling points (P1–P6). Physicochemical variables (water depth, temperature, pH, conductivity, TDS, TSS, dissolved oxygen, turbidity, nitrate, ammonium, phosphorus, and dissolved organic matter) were measured, and the relative abundance of aquatic macrophytes was evaluated. Drivers of change were identified through direct observation and a structured matrix, with a PCoA performed to summarize spatiotemporal trends. Data were analyzed using Principal Component Analysis (PCA), Co-inertia analysis, and Multi-Response Permutation Procedures (MRPP). Significant spatiotemporal variation was observed in physicochemical parameters ($p < 0.05$), with moderate covariation between the two matrices ($RV = 0.47$). A total of ten aquatic macrophyte species were recorded, with higher abundance of *Pontederia crassipes* and *Pistia stratiotes* in T1, and *Hydrocotyle ranunculoides* and *Bacopa monnieri* in T2. The most relevant drivers of change were solid waste, livestock grazing, organic contamination, and urban expansion. Spatial heterogeneity was observed in the drivers of change affecting the Santa Rosa wetland, forming a mosaic of areas with different impact profiles. Despite multiple anthropogenic pressures, the Santa Rosa wetland maintains a limnological structure and a functionally coupled macrophyte community, evidencing ecological resilience to environmental degradation. The observed covariation between physicochemical conditions and vegetation confirms the persistence of essential ecological processes, even within an altered urban context. This study demonstrates that integrating biotic components, limnological variables, and drivers of change is fundamental to understanding and monitoring the ecological dynamics of urban wetlands along the Peruvian coast.

Keywords: aquatic plants; drivers of change; physical-chemical limnology; spatiotemporal variation; Santa Rosa wetland

1. Introduction

Wetlands are highly productive ecosystems that provide essential ecosystem services, such as hydrological regulation, pollutant purification, and habitat provision for a wide variety of species, particularly adapted to their hydrological dynamics [1]. They also act as carbon sinks and store CO₂

in their biomass and sediments, thereby helping to mitigate climate change [2]. Their ability to retain sediments and nutrients prevents eutrophication, leading them to be referred to as the "kidneys of the landscape" [3]. These ecosystems cover between 8.9% and 9.5% of the Earth's surface and are home to remarkable biological diversity, including endemic and endangered species [4]. However, since 1700, nearly 3.4 million km² of wetlands have been lost, mainly due to land use change; in the last 150 years, more than 50% have been degraded by urban and agricultural expansion, while pollution from fertilizers and pesticides has deteriorated water quality and affected biodiversity, including aquatic macrophyte habitats [5–8].

The ecological functioning of wetlands is intrinsically linked to the seasonality of the hydrological cycle, physicochemical limnology of the water, and structure of aquatic macrophyte communities [9–12]. Hydrological regimes regulate seasonal fluctuations in water depth, generating variations in physicochemical limnology, redox conditions, and biogeochemical cycles that control nutrient availability [11,13,14]. Water hydrochemistry and seasonality modify pH, conductivity, salinity, and temperature, affecting the biotic composition and capacity of wetlands to purify water, maintain biodiversity, and provide ecosystem services [15,16].

The aquatic macrophyte community includes freshwater photosynthetic organisms that are visible to the naked eye and can be found as emergent, floating, permanently submerged, or periodically submerged [17]. Their role in ion absorption and transport between sediment and the water column is key to the nutrient cycle and carbon dynamics, influencing dissolved oxygen concentration, nutrient availability, and water quality [9,18,19]. Likewise, their primary production supports multiple trophic levels, and their physical structures provide habitats, shelters, and substrates for various organisms [19,20]. This multifunctionality contributes to ecosystem stability and resilience to disturbances [21,22].

The composition, distribution, and abundance of aquatic macrophytes respond to the interaction of abiotic, biotic, and anthropogenic factors. Among the main hydrological factors, the intensity, duration, and frequency of high and low water levels determine water volume and habitat availability [12,19,21]. Similarly, variability in nutrients, pH, turbidity, and conductivity, together with biotic processes such as competition and herbivory, regulate the richness and dominance of macrophyte species [18,20,23,24]. Eutrophication, fragmentation, and anthropogenic impacts alter these processes to varying degrees [22,25–27].

The wetlands of the Peruvian Pacific are unique ecosystems in the arid subtropical desert, shaped by the interaction between natural processes, such as marine intrusions, El Niño events (ENSO) and exfiltration from coastal aquifers, and human activities, including urban and agricultural runoff, resulting in a complex and dynamic hydrological regime [28–31]. The Santa Rosa wetland, the subject of this study, is one of the most important on the central Peruvian coast from a scientific perspective and is characterized by the highest reported floristic diversity among the coastal wetlands of the Department of Lima, with well-structured communities representative of different functional types of macrophytes [32–34]. Although studies have been conducted on the diversity of the Peruvian Pacific wetlands, mainly on flora and avifauna [34–36], limnological knowledge, particularly regarding the relationship between the physicochemical parameters of water and biota, remains poorly resolved. Previous studies addressing the physicochemical characteristics of water in this system have been spatially restricted and temporally discontinuous, precluding robust assessments of seasonal and interannual variability [37–39], and studies that integrate relationships with aquatic biota are mostly limited to benthic invertebrates [40–42]. While some relationships between physicochemical limnology and aquatic macrophytes have been explored [43,44], the role of physicochemical parameters as determinants of the structure of this community and its spatiotemporal dynamics in urban wetlands represents a critical information gap, which is particularly relevant given the increasing degradation of these environments by anthropogenic activities that compromise their diversity and ecosystem services [32,45–48].

In this context, the present study aimed to evaluate the spatiotemporal dynamics of the aquatic macrophyte community of the Santa Rosa wetland during summer (March) and winter (September)

of 2022, determine its relationship with the physicochemical parameters of the water, and characterize the most important drivers of change. We hypothesize that hydrological seasonality drives significant variation in water physicochemical parameters and in the composition and percent cover of aquatic macrophyte assemblages.'

2. Materials and Methods

2.1. Study Area

The Santa Rosa wetland is located in the district of Chancay, Huaral, Lima region, Peru (Figure 1). Bordered by El Cascajo (north) and Salinas (east) hills, the agricultural lands of Peralvillo and Salinas Altas (south), and the Pacific Ocean (west), it includes a main lake of approximately 17.5 ha and secondary wetlands [49,50]. Its hydrological regime depends on an irrigation canal derived from the Chancay River and the exfiltration of groundwater recharged by agricultural irrigation [31,49]. The maximum water depth occurs between August and October, decreasing towards summer, when Chancay River floods raise it slightly [41]. The wetland features diverse habitats and plant formations: the main body of water, reed beds dominated by *T. domingensis*, reed beds dominated by *S. americanus*, beach areas, unvegetated areas, mixed meadows associated with agricultural and urban areas, cleared areas affected by human activities and shrubby areas [51]. Since 2020, it has been classified as an Environmental Conservation Area under municipal management (Ordinance No. 013-2020-MPH-CM).

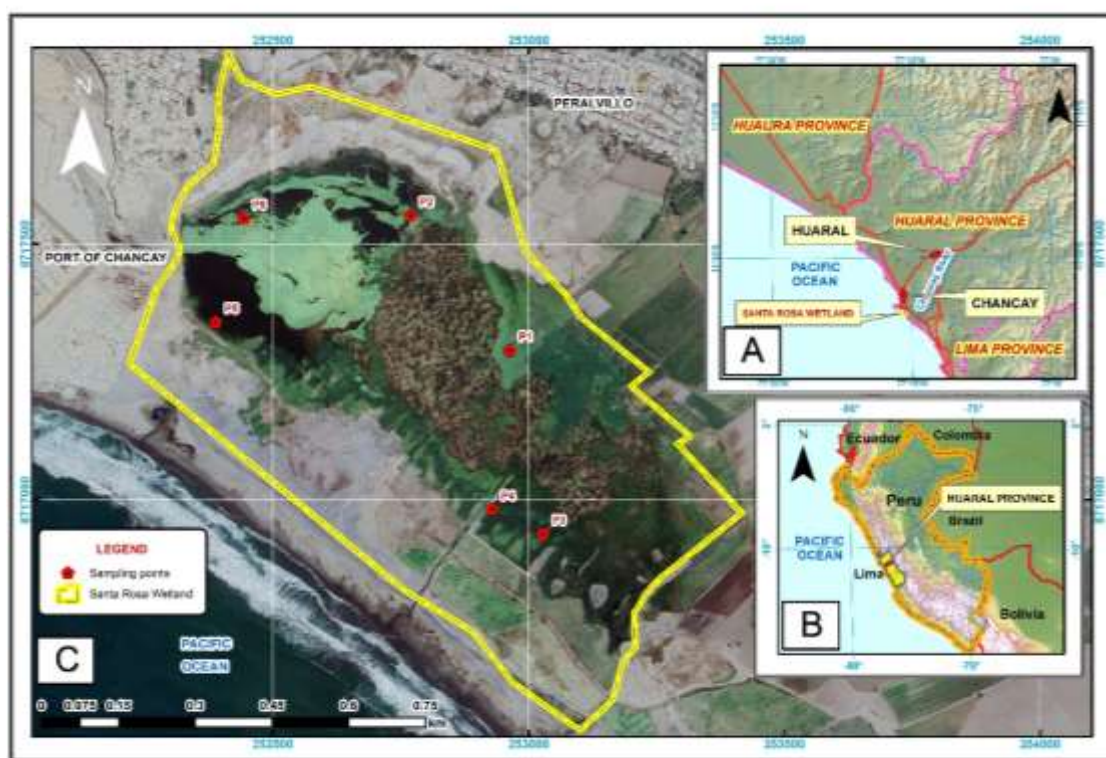


Figure 1. Location of the study area. (A and B) Geographic location in the province of Huaral, district of Chancay, Lima, Peru. (C) Santa Rosa wetland environmental conservation area with sampling points (P1–P6).

2.2. Sampling Design

Six sampling points (P1–P6) were established (Figure 1). Sampling was carried out during two contrasting periods of the hydrological cycle: March 2022 (summer season, T1) and September 2022 (winter season, T2).

P1 is located in an area influenced by the irrigation canal derived from the Chancay River, which receives agricultural and urban effluents, with a predominance of *Pontederia crassipes* (Mart.). P2 was located at the eastern end of the main lagoon and is covered with *Bacopa monnieri* (L.) Wettst and *P. stratiotes*. P3 is a seasonally saturated area with heterogeneous and seasonal vegetation of *T. domingensis*, *P. crassipes*, and *S. americanus*. P4 corresponds to a deep drainage channel where *P. crassipes* is conspicuous and the sediments are thick. P5 and P6, at the western and central ends of the lagoon, respectively, are areas with seasonally variable depths and accumulation of organic matter, dominated by *P. stratiotes*, *B. monnieri*, and *H. ranunculoides*.

2.3. In situ Analysis of Physicochemical Parameters

Depth was measured using a graduated ruler with an accuracy of 1 mm. Physicochemical limnological parameters were recorded in the surface layer of the water (0–20 cm), following the National Protocol for Water Resource Monitoring [52]. The temperature (°C) (Standard Method 2550), pH (Standard Method 4500-H+), electrical conductivity (µS/cm) (Standard Method 2510), total dissolved solids (TDS), and dissolved oxygen (DO) (Standard Method 4500-O) were measured using a YSI Pro multiparameter meter. Turbidity was determined using a Lutron LT-TU2016 turbidimeter (Standard Method 2130 B), while total suspended solids (TSS) were measured with a Hach DR900 photocolormeter (Standard Method 2540). All measurements were taken between 10:00 a.m. and 2:00 p.m. to reduce diurnal variability in the physicochemical limnological parameters. Determinations were made following the Standard Methods for the Examination of Water and Wastewater [53]. For nutrient analysis, 500 mL of surface water was collected at each sampling point, selecting representative and homogeneous areas and avoiding substrate disturbance. The samples were stored at 4 °C for transport and subsequent processing in the laboratory. Phosphate concentration was determined using the ascorbic acid method with a Hanna HI3850 photocolormeter (Standard Method 4500-P E), ammonium using the Nessler method with a Hanna HI733 photocolormeter (Standard Method 4500-NH3), and nitrate using the cadmium reduction method with a Hach DR900 photocolormeter (Standard Method 4500-NO3-E). Dissolved organic matter was determined by gravimetry, using 0.45 µm glass fiber filters, vacuum filtration, and subsequent incineration of volatile solids at 550 °C in a muffle furnace for 2 h [54].

2.4. Aquatic Macrophytes Abundance Determination and Sample Collection

2.4.1. Determination of the Relative Abundance of Aquatic Macrophytes

To estimate the relative abundance of aquatic macrophytes 0.5 m² quadrats were used by applying a quantitative method based on direct coverage estimates [55].

2.4.2. Species Identification of Aquatic Macrophytes

Aquatic macrophytes were collected at each sampling point and preserved in polyethylene bags with formalin. Identification was based on specialized literature [56] and taxonomic checklists [33,34]. The specimens were deposited in the Herbarium of the Natural History Museum of Ricardo Palma University.

2.5. Identification and Classification of Drivers of Change (DOC)

The approach proposed by Sarkar et al. [57] and adapted by Aponte et al. [32] was applied. In the case of the Santa Rosa wetland, specific modifications were incorporated, and the recommendations from the recently developed methodological framework for coastal wetlands in

Peru [46] were also considered in the interpretation of the data. DOCs were classified as direct (immediate physical and chemical impacts) and indirect (sociopolitical, economic, and cultural factors that modulate direct drivers). Direct DOCs included: uncontrolled urban growth (CUD); agricultural (DGA) and livestock (DGP) degradation; introduction of exotic species (IEE); chemical (COQ), organic (CORO), and microbiological (COM) contamination; domestic (RSS) and construction (RSC) solid waste; landfill and drainage (SDE); presence of farms (PGR); effluents (EFL); and other disturbances (e.g., undermining or extraction) (OTP). The only indirect DOC considered was poor management and inadequate governance policies (GMI). Identification was carried out through direct observation at the six sampling points with photographic recording and GPS georeferencing, based on parallel research and a literature review. The analysis was performed during T1 and T2.

2.6. Data Analysis

Principal coordinate analysis (PCoA) was performed using the vegan package in R [58] to evaluate the spatiotemporal variation of the DOCs. Matrices were constructed with the physicochemical parameters and relative abundance of macrophytes by season (T1 and T2) and sampling point (P1–P6), which were summarized in tables and graphs. The relationship between the environmental and biological matrices was evaluated using Spearman's correlation (ρ), considering the value of the statistic and its significance ($p < 0.05$). Physicochemical data were normalized, and the biotic matrix was transformed using the Hellinger procedure, excluding species with a single occurrence [59].

Principal component analysis (PCA) was used to summarize variability and determine spatiotemporal patterns. The significant axes of the PCA were analyzed using multiple response permutation analysis (MRPP) in Vegan package, considering seasons and sampling points as factors of variability [60,61]. The significant axes of an ordination analysis concentrate on the variability of a data matrix and identify the variables that explain it, that is, those most correlated with the axes, allowing statistical inference about this relationship [59]. The relationship between the matrices was analyzed by co-inertia analysis using the ade4 package [62,63]. Co-inertia assesses the covariation of the significant axes of PCA, quantifying shared inertia through the RV coefficient as a measure of the association between both matrices [59]. All analyses were performed using R and RStudio software [64,65].

3. Results

3.1. Spatiotemporal Variation

3.1.1. Macrophytes

Ten species of aquatic macrophytes were recorded: *H. ranunculoides*, *P. crassipes*, *P. stratiotes*, *Azolla filiculoides* Lam., *B. monnieri*, *Ludwigia peruviana* (L.) H. Hara, *S. americanus*, *L. gibba*, *Nasturtium officinale* W. T Aiton, and *Paspalum vaginatum* Sw. Macrophyte coverage generally ranged from 35% to 100%, with significant variations between T1 and T2 at sampling points P1 to P6. At P1, the coverage increased from 88% in T1 to 100% in T2. At P2, there was an increase from 85% in T1 to 100% in T2. In contrast, at P3, coverage decreased slightly from 90% in T1 to 85% in T2. At P4, high levels of coverage were recorded during both periods (95% in T1 and 100% in T2). At P5, coverage showed notable variation, from 60% in T1 to 35% in T2. Finally, at P6, coverage reached 98% in T1 and decreased to 75% in T2 (Figure 2).

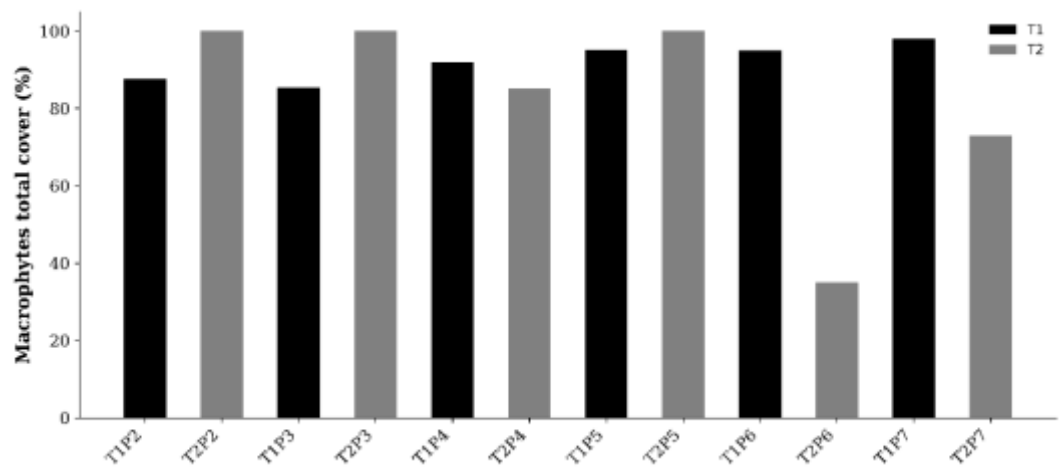


Figure 2. Macrophyte total cover (%) at sampling points (P1–P6) in the Santa Rosa wetland during two seasons: T1 (summer) and T2 (winter).

Regarding the composition and representativeness of aquatic macrophytes per sampling point and season, at P1 dominance changed from *P. crassipes* (65% in T1) to *H. ranunculoides* (55% in T2) (Figure 3A). At P2, *H. ranunculoides* was dominant in T1 (50%); however, in T2, it decreased to 6% and was replaced by *P. stratiotes* (80%) (Figure 3B). At P3, *B. monnieri* dominated in T1 (50%), whereas in T2, it was absent and dominance shifted to *H. ranunculoides* (40%) together with *P. stratiotes* (30%) (Figure 3C). At P4, the dominance of *P. crassipes* (60%) and *L. peruviana* (35%) in T1 decreased in T2, whereas *A. filiculoides* reached 50% (Figure 3D). At P5, the dominance among *B. monnieri* (40%), *H. ranunculoides* (30 %), and *P. stratiotes* (25%) in T1 was reduced in T2 to the exclusive presence of *B. monnieri* (35%) (Figure 3E). Finally, at P6, the shared dominance between *P. stratiotes* (60%) and *H. ranunculoides* (35%) in T1 changed in T2 to the sole presence of *P. stratiotes* (75%) (Figure 3F).

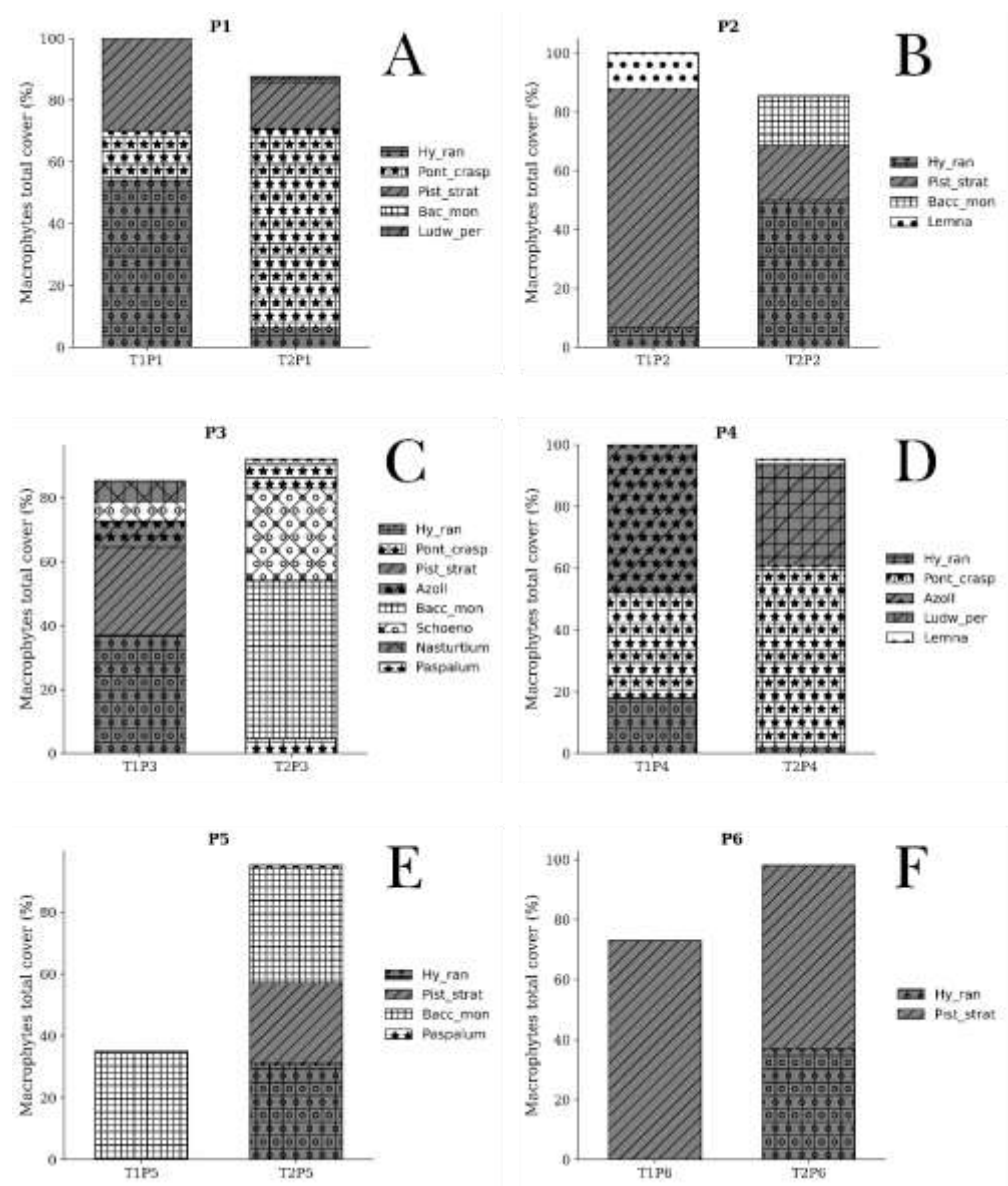


Figure 3. Percentage composition of aquatic macrophytes in Santa Rosa wetland during two seasons (T1: summer, T2: winter) at sampling points: (A) P1, (B) P2, (C) P3, (D) P4, (E) P5, and (F) P6.

3.1.2 Physicochemical Parameters

Spatiotemporal variation was observed in physicochemical parameters (Table 1). Depth increased in T2 compared with T1, except at P4, where it decreased. The temperature decreased in T2 (16.7–22.1 °C) compared with T1 (22–25.9 °C). Dissolved oxygen increased significantly in T2 (3.2–8.2 mg/L), reaching the maximum value at P5 (8.5 mg/L) and the minimum at P2 (3.2 mg/L). The pH remained alkaline in both seasons, with a slight decrease in T2. Conductivity and TDS showed reductions in T2, reflecting a seasonal ionic dilution process. Similarly, TSS and turbidity decreased, with the highest values recorded at P6 (TSS) and P1 (turbidity) during T1, and the lowest at P4 in T2. Regarding nutrients, nitrates showed marked spatial variation in both seasons, while ammonium and phosphates tended to increase in T2, with maxima at P1 and P3 for ammonium, and at P3 for phosphates. Dissolved organic matter (DOM) showed a heterogeneous pattern among sampling points, with increases at P3 and P5 and decreases at P1, P2, and P4 in T2.

Table 1. Values of physicochemical parameters recorded at the sampling points in Santa Rosa wetland during two seasons: T1 (summer) and T2 (winter).

Sample Points	pH		Conductivity (μS/cm)		TDS (mg/L)		DO (mg/L)		Temperature (°C)		Depth (m)		TSS (mg/L)		Turbidity (NTU)		PO ₄ ³⁻ (mg/L)		NH ₄ (mg/L)		NO ₃ (mg/L)	
	T1	T2	T1	T2	T1	T2	T1	T2	T1	T2	T1	T2	T1	T2	T1	T2	T1	T2	T1	T2	T1	T2
P1	8	7.45	1610	1166	505	788	0.8	6	25	21.8	0.12	0.12	52	50	57	40.77	0.605	0.66	1.54	3.43	7	6
P2	8.3	7.13	3000	2740	1260	1940	0.4	3.2	27	20.5	0.08	0.19	50	8	50	9.47	0.9	1.06	1.75	1.26	7.5	7
P3	7.9	7.43	1770	1401	907	940	0.5	3.4	22	22.1	0.13	0.20	19	45	25	45.92	0.785	1.28	1.49	3.03	0.05	3
P4	7.9	7.42	1360	992	610	670	0.3	4.18	23	19.9	0.75	0.39	19	4	18	10.51	0.97	0.29	1.55	0.81	2	4
P5	8.5	8.72	3280	1632	1968	1095	0.5	8.2	23.8	19.5	0.40	0.84	56	56	56	34.87	1.03	1.65	1.81	1.22	9	0.05
P6	8.1	8.06	2045	1735	1227	1155	0.3	6.5	25.9	16.7	0.40	0.50	74	20	72	12.8	1.05	1.54	1.9	0.97	7	4

3.2. Spearman’s Correlation Matrix and Drivers of Change

3.2.1. Spearman’s Correlation Matrix

A positive correlation was observed between electrical conductivity and TDS ($\rho = 0.88$), and among turbidity, TSS, and DOM ($\rho \geq 0.73$). In contrast, dissolved oxygen decreased as temperature increased ($\rho = -0.84$). *P. crassipes* and *L. peruviana* were positively correlated ($\rho = 0.72$). Regarding the physicochemical-macrophyte relationship, *P. crassipes* was negatively correlated with conductivity ($\rho = -0.67$), TDS ($\rho = -0.87$), and phosphates ($\rho = -0.78$) (Figure 4).

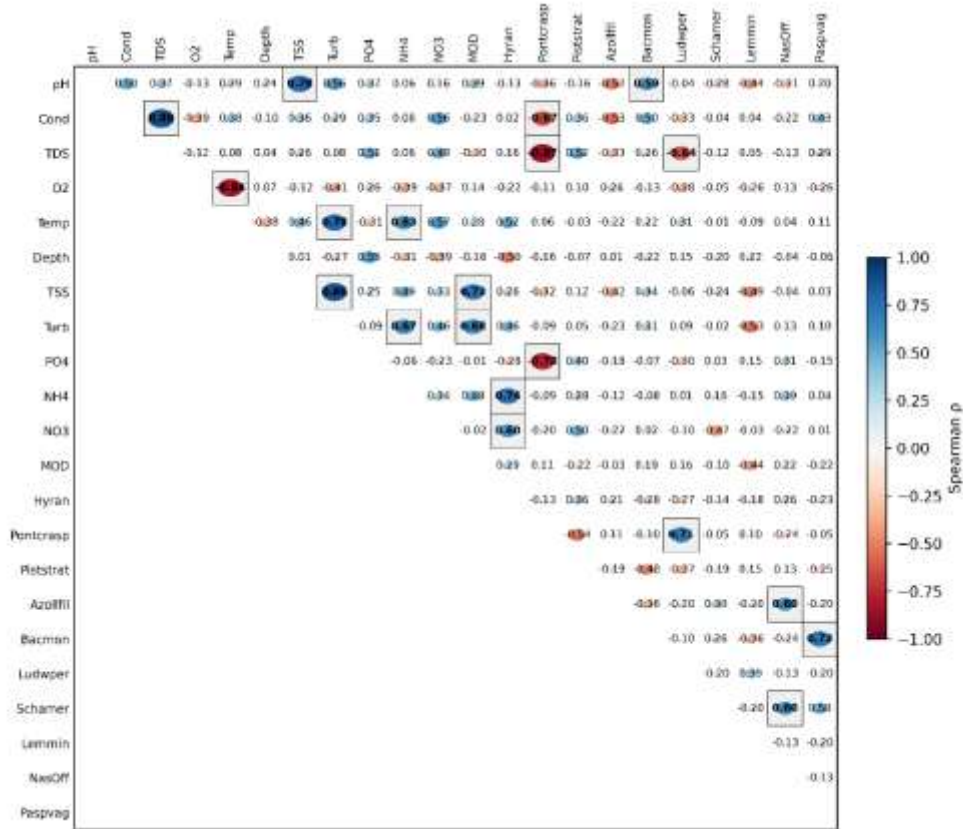


Figure 4. Spearman's correlation matrix of association between biotic and abiotic variables.

3.2.2. Drivers of Change

The analysis of drivers of change (DOC) in the Santa Rosa Wetland revealed a spatially heterogeneous pattern of impact (Table 2). P4 had the highest number of DOCs (12), followed by P1 and P5 (9), P6 (7), and P2 and P3 (6 each), respectively. Livestock degradation (DGP), characterized by cattle, sheep, goat, and pig farming, was present at all sampling points. Similarly, introduction of exotic species (IEE), such as dogs and free-grazing livestock (cattle, sheep, and goats) occurred at all locations. Organic contamination (CORG), characterized by food and agricultural waste, livestock manure, urban effluents, as well as microbiological contamination (COM), indicated by the presence of thermotolerant coliforms, were also recorded at all sampling points. Governance failures (GMI), including poor inter-institutional participation and coordination leading to deficiencies in the effective protection of wetlands, were considered common to all sampling points. Chemical contamination (COQ), characterized by the use of pesticides and fertilizers, was recorded at P1, P4, P5, and P6. Solid waste (RSS) was found at P4, P5, P6, and P1 during T1, and construction solid waste (RSC) and burial/desiccation waste (SDE) were recorded at P1, P4, and P5. Other DOCs showed localized distribution: uncontrolled urban growth (CUD) was recorded only at P4; agricultural

degradation associated with land use change for agriculture (DGA) at P3 and P4; pig and cattle farms (PGR) in P2; effluents (EFL) at P1, and other disturbances (OTP), such as alteration of residence time due to drainage excavation, only in P4 in T2.

Table 2. Drivers of change identified at the sampling points.

DOC	CUD	DGA	DGP	IEE	COQ	CORG	RSS	RSC	SDE	PGR	COM	GMI	EFL	OTP
T2P1	0	0	1	1	1	1	0	1	1	0	1	1	0	0
T2P2	0	0	1	1	0	1	0	0	0	1	1	1	0	0
T2P3	0	1	1	1	0	1	0	0	0	0	1	1	0	0
T2P4	1	1	1	1	1	1	1	1	1	0	1	1	0	1
T2P5	0	0	1	1	1	1	1	1	1	0	1	1	0	0
T2P6	0	0	1	1	1	1	1	0	0	0	1	1	0	0
T1P1	0	0	1	1	1	1	1	1	1	0	1	1	1	0
T1P2	0	0	1	1	0	1	0	0	0	1	1	1	0	0
T1P3	0	1	1	1	0	1	0	0	0	0	1	1	0	0
T1P4	1	1	1	1	1	1	1	1	1	0	1	1	0	0
T1P5	0	0	1	1	1	1	1	1	1	0	1	1	0	0
T1P6	0	0	1	1	1	1	1	0	0	0	1	1	0	0

* Uncontrolled urban growth (CUD), Agricultural (DGA) and Livestock (DGP) degradation, Introduction of exotic species (IEE), Chemical (COQ), Organic (CORG), and Microbiological contamination (COM), Solid waste (RSS), Construction waste (RSC), Burial and drying (SDE), Presence of farms (PGR), Effluents (EFL), Governance failures associated with poor management and inadequate policies (GMI) and Other disturbances (alteration of residence time due to drainage excavation) (OTP). Note: 1 = presence of driver; 0 = absence.

3.2.3. Principal Coordinates Analysis (PCoA)

The ordination based on the drivers of change (DC) matrix revealed spatial heterogeneity in the pressures affecting the Santa Rosa Wetland (Figure 5). Sampling points formed discrete and well-defined groups, in which the primary source of variation was spatial location rather than temporal dimension, suggesting persistence of pressure profiles at each point throughout the analyzed period. Axis PCoA1 separated P2 and P3 from the remaining sampling points, while axis PCoA2 distinguished P3 from P4. Four subgroups emerged based on DOC incidence: one comprising P1, P5, and P6, which share a similar DOC profile, and three points (P2, P3, and P4) that clustered separately, each exhibiting a distinctive set of drivers of change. Collectively, these results indicate that driver variability in the wetland is predominantly spatial, resulting in a mosaic of zones with differentiated impact profiles.

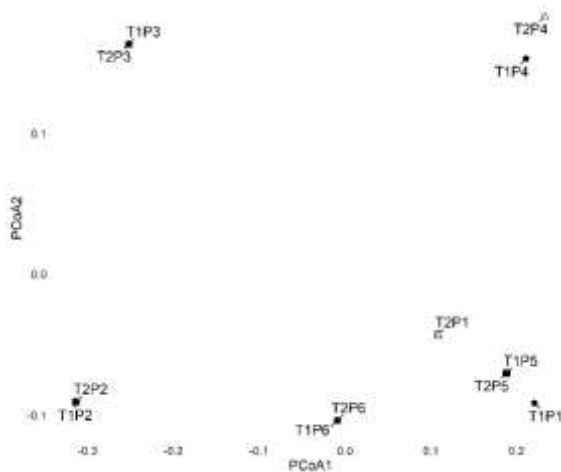


Figure 5. Principal Coordinates Analysis (PCoA) ordination of sampling points based on the drivers of change (DOC).

3.3. Relationship Between Biotic and Abiotic Matrices

3.3.1. Principal Component Analysis (PCA)

The first three principal components (PC1, PC2, and PC3) of the principal component analysis (PCA) of the abiotic matrix explained 74.55% of the total variability (PC1: 34.47%; PC2: 21.06%; PC3: 19.02%). PC1 retained the variability of turbidity, temperature, and total suspended solids ($q = -0.941$, -0.864 , and -0.850 , respectively), showing a temporal gradient of change. PC2 concentrated the variability of conductivity and total dissolved solids ($q = 0.794$ and 0.792 , respectively), showing a gradient of ionic concentrations between sampling points and seasons. PC3 retained the variability of pH and phosphates ($q = -0.750$ and -0.872 , respectively), associated with a gradient of acidity and nutrient availability (Figure 6). The PCA of the biotic matrix explained 76.87% of the variability in the first three components (PC1: 31.20%; PC2: 27.15%; and PC3: 18.51%). PC1 retained the variability of *P. stratiotes*, *P. crassipes*, and *L. peruviana* ($q = -0.830$, -0.788 , and 0.728 , respectively), reflecting a spatial gradient associated with dominant floating and emergent species. In PC2, *B. monnieri* and *S. americanus* concentrated their variability ($q = -0.891$ and 0.625 , respectively), characterizing a spatiotemporal pattern of occurrence in shallower environments. PC3 was associated with the occurrence of *A. filiculoides* ($q = 0.875$), indicating favorable conditions for this species (Figure 7). Statistically significant differences were found in the MRPPs between seasons (PC1) and sampling points (PC3) of the abiotic matrix ($p < 0.04$ and $p < 0.037$, respectively) and between sampling points for PC2 of the biotic matrix ($p < 0.047$).

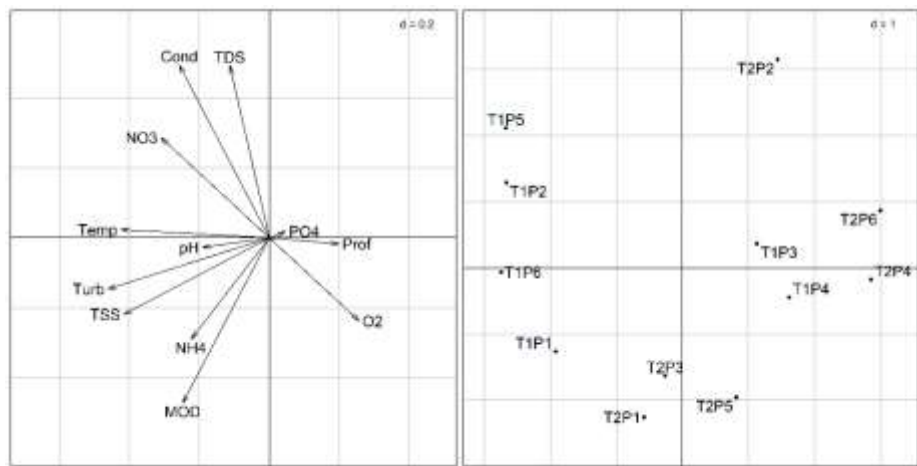


Figure 6. Principal Component Analysis (PCA) for physicochemical variables.

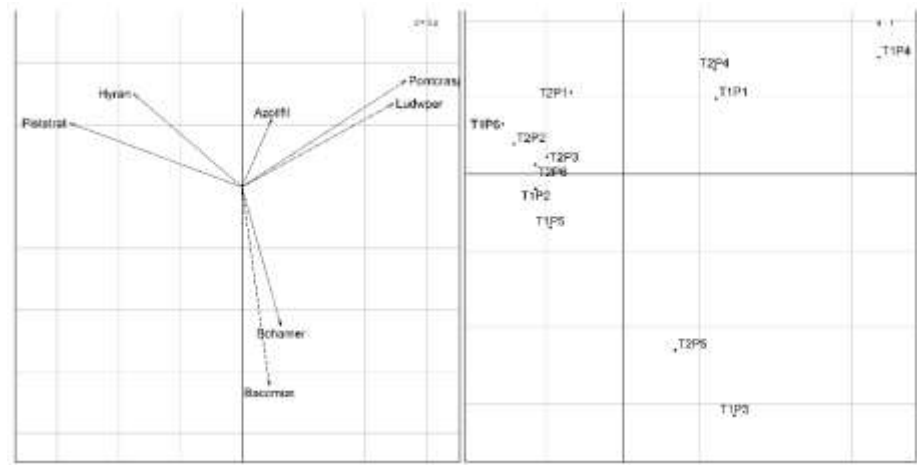


Figure 7. Principal Component Analysis (PCA) for macrophytes.

3.3.2. Co-Inertia

The co-inertia analysis obtained a total inertia of 8.693, retaining 88.97% of the co-inertia (E1: 50.48%, E2: 25.84%, and E3: 12.65%). The correlation (covariation) between both matrices was high for axes 1 and 2, and moderate for axis 3 ($\rho E1 = 0.86$, $\rho E2 = 0.82$, $\rho E3 = 0.67$). An RV coefficient of 0.468 was obtained, representing moderate covariation between the matrices. A main gradient (E1) was observed, defined by TDS, Cond, TSS, Turb, PO_4^{3-} , NO_3^- (positive correlation), and Depth (negative correlation). E2 showed a gradient of pH and PO_4^{3-} (positive correlation) and NH_4^+ and NO_3^- (negative correlation). The axis structure reflects the pattern observed in the PCA, with the dilution of the main ions as the depth increased. *P. stratiotes* showed covariation with TDS, Cond, NO_3 , PO_4^{3-} , and pH. *B. monnieri* was associated with pH and PO_4^{3-} , whereas *H. ranunculoides* was more related to shallow environments with high concentrations of NH_4^+ , TSS, and Turb. *A. filiculoides* was associated with deeper and less mineralized environments, whereas *P. crassipes* was more related to less mineralized environments (Figure 8). Good agreement was observed between the biotic and abiotic matrices in T2P3, T2P2, T1P6, and T2P5 (short arrows) (Figure 9), while in T2P6, T1P1, T1P5, T1P3, and T2P4, disagreement was observed between both matrices (long arrows). T1P2, T1P5, and T1P6 were associated with the Cond, TDS, pH, and PO_4^{3-} gradient and the presence of *P. stratiotes* and *B. monnieri*; T1P4 and T2P4 were associated with low mineralization and the presence of *P. crassipes* and *A. filiculoides*, whereas T2P1 and T2P3 were associated with *H. ranunculoides* and high concentrations of NH_4^+ , TSS, and Turbidity. In general, a pattern of ionic dilution was observed with increasing depth from T1 to T2, and a temporal gradient of change in physicochemical limnology and aquatic macrophytes (Figures 8 and 9). Although moderate covariation was observed between the matrices, it was not statistically significant ($p > 0.05$) owing to variability within each sampling point.

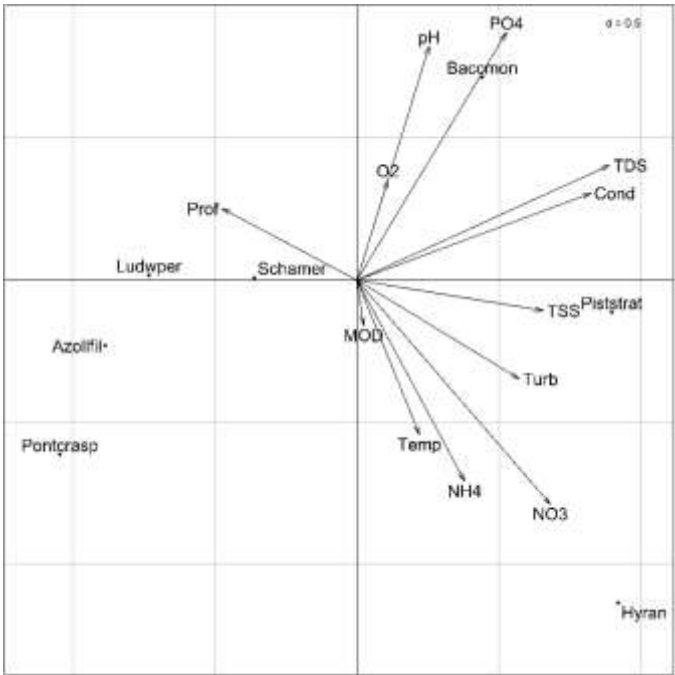


Figure 8. Co-inertia biplot (axes 1–2): covariance-optimized structural matching between limnological variables and macrophyte assemblages.

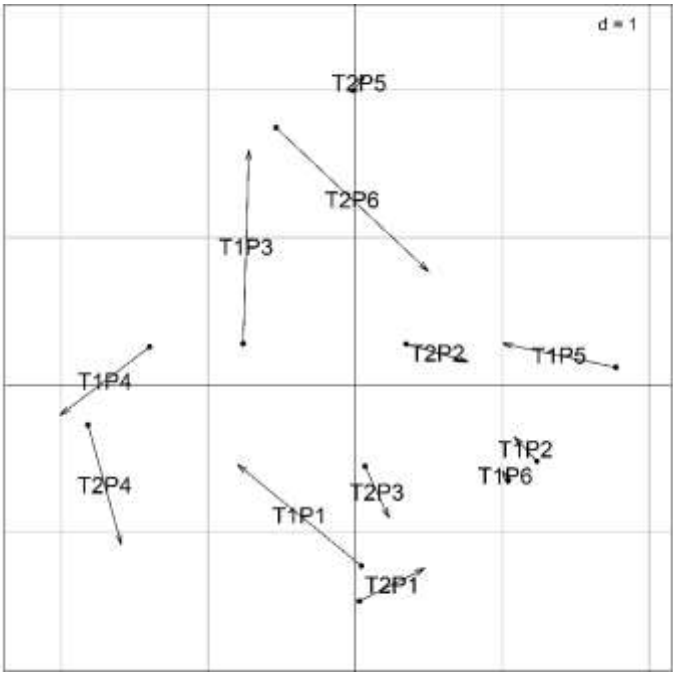


Figure 9. Temporal trajectories showing changes between sampling periods.

4. Discussion

The ecological dynamics of wetlands are characterized by a hierarchical interaction among the hydrological regime, physicochemical limnology, and structure of the aquatic macrophyte community, with linkages that vary spatially and temporally [9,13,18]. This relationship is not unidirectional; aquatic macrophytes and the consequences they have on physicochemical heterogeneity can feed back into the system, altering or buffering the hydrological regime [17,19,20]. The alternation of these processes defines a wetland as ecological systems [12], and it is within this dynamic that anthropogenic impacts become evident [22,23,66].

The Santa Rosa wetland is severely affected by various drivers of change that compromise its integrity, as are most coastal wetlands on the Lima, which are predominantly urban [32]. However, the fundamental ecological pattern of a wetland, the spatiotemporal variability of physicochemical limnology, and the macrophyte community modulated by the different phases of hydrological seasonality are still recognizable, with some reservations, as demonstrated in this study, which is the first of its kind in Peruvian coastal wetlands.

The results show that the Santa Rosa wetland is subject to a combination of direct and indirect drivers of change that act synergistically and generate cumulative pressures on its ecological integrity. The simultaneous presence of factors, such as waste accumulation, livestock farming, and the introduction of exotic species, has been widely documented as one of the main causes of tropical wetland degradation [57,67]. These direct drivers act on habitat structure and water quality, whereas indirect factors, such as poor governance and unplanned urban expansion, perpetuate these impacts by weakening institutional capacities to mitigate them [32,68]. Evidence suggests that when these drivers coexist spatially, ecological effects intensify, hindering natural recovery processes [69].

In the Santa Rosa wetland, physicochemical limnology showed marked seasonal variations, with higher concentrations of total suspended solids (TSS), turbidity, temperature, conductivity, and total dissolved solids (TDS) during the summer period (T1), attributable to the influence of the irrigation canal in T1 and the ionic dilution effect associated with greater water depth in T2. This pattern is characteristic of shallow wetlands with seasonal connectivity [13,70]. However, the temporal component of the hydrological regime exerts a more decisive control over the limnological dynamics of the system [9,21], which, in the present study, is reflected in the increase in depth and seasonal ionic dilution. It is important to note that the nutrient concentrations and physicochemical

parameters recorded, which may seem high compared to pristine wetlands, constitute the current reference condition for a system embedded in an agricultural-urban matrix. Rather than anomalies, these values reflect the current hydrochemical regime that conditions the seasonal variability of the wetland. The ionic content of this system is modulated by local processes (both natural and anthropogenic) and by the specific hydrological characteristics of the Santa Rosa wetland basin. In general, the ionic concentrations (conductivity and TDS) of Santa Rosa wetland are lower than those of other coastal wetlands, such as the Pantanos de Villa, Humedales de Ventanilla, and wetlands in La Libertad region [37,40,42,43]. The conductivity values recorded in the Santa Rosa wetland (3280–940 $\mu\text{S}/\text{cm}$ in T1 and T2) were below the limiting thresholds for dominant floating species, such as *P. stratiotes* and *P. crassipes* [71,72]. Regarding dissolved oxygen, the recording of critical hypoxia thresholds in T1 ($< 2\text{mg}/\text{L}$) and recovery to physiologically acceptable levels for macrophytes and biota in general in T2 [71] shows the alternation of states and their amplitude between seasons. This pattern is particularly evident at some sampling points, which is characteristic of structurally complex wetlands with lacustrine and palustrine sectors [18,20].

Between T1 (summer) and T2 (winter), seasonal replacement of *P. crassipes* by *H. ranunculoides*, of *P. stratiotes* by *B. monnieri*, and of *B. monnieri* by *P. stratiotes* and *H. ranunculoides* was observed, reflecting a relative increase in marsh species in response to water retreat. However, this pattern varies among sectors of the wetland, where geomorphological heterogeneity and water connectivity modulate the magnitude of the coverage change between sampling points. This pattern coincides with observations in other neotropical and urban aquatic systems, where macrophyte communities maintain a stable functional composition in the face of broad environmental gradients, and the homogenization of physical and chemical conditions limits floristic turnover and favors the dominance of a few species [73]. These results are consistent with studies showing that the seasonal dynamics of aquatic macrophytes in shallow wetlands respond strongly to hydrological regimes, especially the flood and retreat cycle, which favors marsh species during periods of decreasing water depth [21,74]. The alternation in dominance between floating and marsh species reflects adaptive mechanisms in response to water variability and habitat availability, which have been documented in neotropical and intertropical systems with marked seasonality [24,70].

The relationship between physicochemical limnology and the distribution of aquatic macrophytes in the Santa Rosa wetland was particularly evident in specific areas. The ionic concentration gradient (pH, conductivity, TDS) was associated with the dominance of *P. stratiotes* and *B. monnieri*, whereas *H. ranunculoides* was limited by increasing depth. In contrast, *P. crassipes* showed greater affinity for waters with lower pH, TDS, and conductivity. Likewise, a moderate covariation structure was evident between the biotic and abiotic matrices, reflecting specific patterns of change in particular sectors and macrophyte species across seasons and sampling points. Although these patterns were not consistent across the entire matrix, the relationship was not statistically significant. These findings are consistent with previous studies that have documented the sensitivity of aquatic macrophytes to environmental gradients, especially in shallow systems, where fluctuations in pH, nutrients, and conductivity strongly influence species distribution [66]. The specific association of *P. crassipes* with less mineralized waters and *P. stratiotes* with more mineralized environments reflects contrasting ecophysiological strategies in response to environmental conditions [20,22]. In the lagoon sector of the Santa Rosa wetland, Muñoz et al. [75] described the dynamics of *P. stratiotes*, the dominant floating species in that environment, whose growth is influenced by local concentrations of ammonium, phosphate, and phosphorus, highlighting the relevance of physicochemical limnology in the structuring of aquatic macrophytes in wetlands. Likewise, the influence of phosphorus on species assembly coincides with reports indicating that increased nutrient concentrations can induce abrupt changes in the dominance of floating or marsh life-forms [25,76,77]. In the Santa Rosa wetland, agricultural activity has been suggested to promote an increase in the coverage of *P. crassipes*, *P. stratiotes*, and *Lemna gibba* [50,78], with high values of chemical oxygen demand (COD), biological oxygen demand (BOD), total nitrogen (TN), and total phosphorus (TP) being recorded [44,79]. The concentrations of nitrate, ammonium, and phosphate in the Santa Rosa Wetland showed a spatial

and temporal gradient of nutrients, associated with variations in the composition and coverage of macrophytes. Although there are no previous records of the degree of trophic status and its progressive increase, the levels recorded in 2022 suggest a system tending toward eutrophication and hypertrophy, with spatial and temporal variability. This condition is not an anomaly, but rather a hydrochemical pattern characteristic of coastal wetlands immersed in agricultural-urban matrices [38,80,81]. The structure of the plant community responds to nutrient availability by assimilating excess nutrients and maintaining ecosystem activity despite anthropogenic pressure [26,82]. Although the results allowed the identification of associations between nutrient gradients and macrophyte distribution, it was not possible to establish retrospective causal relationships with respect to the eutrophication of the system.

The variability in co-inertia at specific sites suggests that unmeasured factors such as herbivory, sedimentation associated with local hydrological regimes, and other localized drivers of change could modulate community structure. In particular, P3 and P4 were influenced by agricultural activity, and chemical contamination at P1, P4 and P5 was linked to agricultural effluents and sediment input; additionally, preferential herbivory on *P. crassipes* and *H. ranunculoides*, as observed in the field and documented in the literature [50,83], may modify community responses to limnological variables and seasonality. Thus, the moderate co-inertia between the biotic and abiotic matrices, along with the lack of statistical significance of the RV coefficient despite the observable patterns, stem from the structural complexity of the wetland, which presents lacustrine and palustrine sectors with distinct hydroperiods, connections to agricultural effluents, and anthropogenic pressures that vary in space and time. In addition to the natural complexity of wetlands, local pressures contribute to the lack of concordance between the matrices. Several studies have examined the determinants of aquatic macrophyte community composition across spatial and temporal gradients, yielding results that broadly fall into two categories: (1) those reporting clearly defined causal relationships, typically associated with systems governed by strong structuring factors such as regular hydrosedimentological pulses and well-defined hydrological connectivity [26,77,84,85] and (2) those identifying statistically significant but partially explained patterns, characteristic of systems in which structuring gradients are spatially heterogeneous or temporally variable [24,86,87]. The present study aligns with the latter category, a finding consistent with the inherent hydrological variability and spatial heterogeneity of the Santa Rosa wetland, where the coexistence of lacustrine and palustrine zones generates diffuse environmental gradients that reduce the explanatory power of multivariate approaches [87]. In this context, it should be noted that the RV coefficient, although widely employed as a global measure of association in multivariate ecological analyses, is sensitive to sample size and the number of variables considered [88].

Effective wetland conservation requires understanding of their ecological functioning and the factors shaping their structure and dynamics, including not only the biotic communities they support but also the different subsystems composing them. Nevertheless, reductionist approaches persist in limnological studies, which tend to focus only on main open water bodies such as lagoons or shallow lakes, leaving aside functionally key environments, such as marshlands, floodplains, seasonal plains, and transitional microhabitats [9,10,66]. Previous limnological studies of Peruvian coastal wetlands have focused on the main lagoons and a few shallow environments, overlooking marsh environments [41,42]. Indeed, coastal wetlands such as Santa Rosa constitute "wetlandscapes," that is, mosaic landscapes composed of multiple functional units with specific physicochemical conditions and differential ecological responses [57,89]. The Santa Rosa wetland exhibits marked internal limnological heterogeneity, with marsh and lake sectors showing contrasting physicochemical dynamics. These sectors can be interpreted as differentiated functional patches, the coexistence of which contributes to the structural and functional stability of the wetland, without implying a formal classification of landscape units.

The results show that different sectors of the Santa Rosa Wetland respond differentially to water quantity and quality, which in turn modulates the structure of the macrophyte community. However, this pattern is moderately explained not only by the intrinsic heterogeneity of the wetland but also

by the effect of drivers of change. This finding contributes to understanding the limnology-biota relationship, an aspect scarcely addressed in the literature on Peruvian wetlands, which has mostly favored descriptive or ecological community approaches without examining functional relationships with limnological dynamics [90,91]. This gap limits the ability to diagnose threats, such as drying, hydrological fragmentation, and climate change, which requires an understanding the coupling between abiotic and biotic matrices [27].

This study contributes to the existing body of knowledge by demonstrating that the limnological structure of wetlands cannot be reduced to the main lagoon. Rather, it must be understood as an integrated system, where areas currently undergoing degradation continue to perform key ecological functions. Despite the multiple drivers of change, waste accumulation, livestock farming, introduction of exotic species, and urbanization, the Santa Rosa wetland continues to sustain essential processes such as nutrient retention, habitat provision, and hydrological regulation, demonstrating the persistence of functional integration among temporal dynamics, physicochemical limnology, and aquatic macrophyte communities [57,67]. The findings suggest that the maintenance of critical functions does not depend exclusively on the best preserved areas but also on the interaction between impacted and less impacted sectors, which has direct implications for the design of conservation, restoration, and climate change adaptation strategies [3,12].

Given the increasing degradation of coastal wetlands along the Peruvian Pacific, understanding the relationship among the hydrological cycle, limnology, and aquatic macrophytes, as addressed in this study, is key to redefining conservation priorities, identifying functional thresholds, and guiding interventions toward maintaining fundamental ecological processes, even in highly transformed landscapes. It is also suggested that the most variable sites, or those with a less clear explanatory relationship between biotic and abiotic processes, may be subject to unique local drivers of change. This opens up a particularly important line of research aimed at establishing casual links between the drivers of change and their effect on community-environment coupling. It is recommended that future studies address this question with extended temporal coverage.

5. Conclusions

The Santa Rosa wetland maintains recognizable ecological patterns despite sustained anthropogenic pressures. The cycle of rising and falling water levels remains the primary structuring force of physicochemical limnology, and the aquatic macrophyte community responds coherently to seasonal changes in water depth, ionic concentration, and nutrient availability, evidencing functional coupling between biota and environmental conditions. Drivers of change are predominantly spatial in their distribution, generating a mosaic of differentiated impact profiles that modulate this coupling at local scales. By integrating limnological dynamics, macrophyte community structure, and drivers of change—an approach scarcely applied in Peruvian coastal wetlands—these findings provide a scientific foundation for identifying functional thresholds, guiding conservation strategies in increasingly threatened urban wetland systems along the Peruvian Pacific coast.

Author Contributions: Conceptualization, J.A.-I. and F.R.-C.; methodology, J.A.-I. and F.R.-C.; software, J.A.-I.; validation, J.A.-I. and S.U.-R.; formal analysis, J.A.-I.; investigation, F.R.-C., S.U.-R. and J.A.-I.; resources, J.A.-I.; data curation, J.A.-I. and F.R.-C.; writing—original draft preparation, F.R.-C. and J.A.-I.; writing—review and editing, F.R.-C., J.A.-I. and S.U.-R.; visualization, J.A.-I. and F.R.-C.; supervision, J.A.-I.; project administration, J.A.-I.; funding acquisition, J.A.-I. All authors have read and agreed to the published version of the manuscript..

Funding: This study was conducted as part of the project: Environmental degradation vs. ecosystem response: A case study in the Santa Rosa wetland from a limnological perspective (004-2020-PRO99), winner of the 2020 Cabieses Teaching Seed Fund Grant from the Universidad Científica del Sur, and is part of Flavia Valeria Rivera Cáceda's Bachelor's Thesis in Marine Biology under the guidance of Dr. José Antonio Arenas Ibarra.

Institutional Review Board Statement: Not applicable.

Data: Availability Statement.

Acknowledgments: Materials and equipment acquired by the project and others loaned for use by Terra Aqua Perú S.A.C. were used for field sampling and laboratory analysis. Chemical determinations were performed at Wet Experimental Laboratory No. 104 of the Universidad Científica del Sur. José Antonio Arenas Ibarra used protected hours for research in his capacity as an Associate Researcher at the Universidad Científica del Sur, Director of the Institute of Natural Resources and Ecology, and Director of the Ecology Laboratory at the Universidad Ricardo Palma. The facilities of the Ecology Laboratory of the Faculty of Biological Sciences and their infrastructure and research resources were used for the final draft. Access to academic databases at the Universidad Científica del Sur and Universidad Ricardo Palma were used. The authors would like to thank the National Forest and Wildlife Service (SERFOR) for facilitating the necessary research permits, and Mr. Williams Jurado Zevallos, General Coordinator of the Santa Rosa Chancay Wetland Surveillance Committee, for providing the letter of Prior Informed Consent. Special thanks are extended to James López Visag and Sofía Urrutia Ramírez, Martín Muñoz, Kaory Tinoco, Bruno Reátegui, and Edwin Pinto for their collaboration during fieldwork and laboratory sample processing, and to Dámaso Ramírez for his guidance on field sampling techniques and assistance in the specific identification of aquatic macrophytes.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

TDS	Total dissolved solids
TSS	Total suspended solids
DO	Dissolved oxygen
Cond	Conductivity
Turb	Turbidity
DOM	Dissolved organic matter
DOC	Drivers of change
PCA	Principal Component Analysis
PCoA	Principal Coordinate Analysis
MRPP	Multiple Response Permutation Procedure
CUD	Uncontrolled urban growth
DGA	Agricultural degradation
DGP	Livestock degradation
IEE	Introduction of exotic species
COQ	Chemical contamination
CORG	Organic contamination
RSS	Solid waste
RSC	Construction waste
SDE	Burial and drying
PGR	Presence of farms
COM	Microbiological contamination
GMI	Governance failures associated with poor management and inadequate policies
EFL	Effluents
OTP	Other disturbances (alteration of residence time due to drainage excavation)

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